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Modeling and Optimization of a Vortex Induced Vibration Fluid Kinetic Energy Harvester

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Abstract

In this contribution a fluid kinetic energy harvester excited by vortex induced vibration (VIV) is proposed. In terms of describing and verifying the interaction between the structural and the fluidic domain, a two-way Fluid Structure Interaction (FSI) simulation has been carried out. In order to optimize the harvester, different designs have been investigated to improve the performance. Subsequently, a demonstrator setup for testing the manufactured harvester has been assembled. The experimental results were compared with that of FSI-simulations. By applying the optimized harvester structure, the vortex induced pressure could be enhanced 4 times compared to convetional structures. The results show that the VIV energy harvester deliver 1 µW power output under 2 m/s air flows.

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Keywords: Fluid kinetic energy, Energy harvester, Vortex Induced Vibration, Karman vortex street, Piezoelectricity

1. Introduction

Due to groundbreaking developments in micro and nanotechnology within the last decade, both size and power consumption of micro systems have been reduced. Advances in ultra-low-power electronics lead to a further reduced power consumption of approx. 10 µW - 100 µW [1]. Hence, the application of micro energy harvester as power supply for e. g. wireless sensor network becomes feasible.

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Various micro energy harvester concepts have been intensivly investigated [2,3]. These research groups are focusing on utilizing solar, thermal and vibration energy as sources. In order to improve the environmental adaptability of a specific microsystem such as sensor nodes, other energy sources like fluidic energy have to be taken into account.

According to [3], fluid kinetic energy sources can also provide very reasonable amounts of energy compared to other environmental energy sources. Due to device miniaturization the proportional frictional forces increase and consequently the efficiency of conventional hydro turbine concepts are reduced. Hence, the vortex induced vibration approach was introduced by Taylor [4] to harvest energy out of a water flow. A eel like harvester of 3 m length was designed for converting ocean current into electrical energy. The Pobering group reduced size of such a harvester for the applicatrion to millimeter scale by using microtechnologies [5]. But, due to the lower density of air compared to water, the yield of harvested energy seems to be limited. Therefore, investigations for improved designs to enhance the conversion efficiency of the vortex induced vibration (VIV) energy harvester are needed.

2. Theoretical background

For many applications fluid kinetic energy has to be harvested from a low velocity air flow. Therefore a VIV energy harvester is proposed. It consists of a bluff body and an electromechanical transducer. The fluid flows across the bluff body located in a tube with a certain Reynolds number. According to the Karman vortex street effect, a series of alternating vortices is generated in the wake flow region. Therefore, an unsteady pressure distribution is constituted, which leads to a vibration of a piezoelectric transducer placed behind the bluff body (Fig. 1). Due to the piezoelectric effect, the fluid kinetic energy is finally converted to electrical energy.

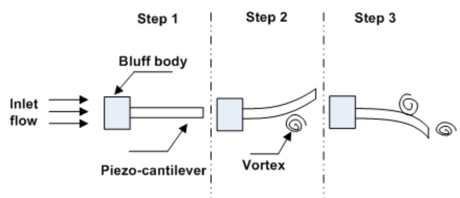

Fig. 1. Scheme of the basic working principle of VIV energy harvester

The pressure related frequency in the wake region is equal to the vortex shedding frequency. It can be described with the diameter of the bluff body D, the flow velocity V and the Strouhal number Sr by:

$$f_{vortex} = \frac{Sr \cdot V}{D} \tag{1}$$

In order to ensure the maximum conversion efficiency, the cantilever transducer has to be excited at its eigenfrequency. Hence, the amplitude of the vortex induced pressure in the wake flow is crucial for a maximum electrical output of the piezoelectric cantilever transducer. Unfortunately, the turbulent flow in the wake is hard to describe analytically with Navier-Stokes equations. But, as suggested in [5] the vortex induced pressure is given by the fluid flow velocity difference. Hence, it can be simplified as a sum of two velocity components, which are the flow along the downstream with a laminar velocity V_{lam} and rotational flow with a velocity V_{rot}. According to the Bernoulli equation, the vortex induced pressure p applied to the surface of the cantilever can be written as:

$$p = \frac{\rho}{2} V_{lam}^2 - \frac{\rho}{2} \left(V_{lam} - V_{rot} \right)^2 \tag{2}$$

where ρ is the air density. Presume the rotational velocity V_{rot} is proportional to the flow velocity of laminar flow V_{lam}, by substituting V_{rot} with the V_{lam}/k the equation could be rewritten as:

$$p = \frac{\rho}{2} \left[V_{lam}^2 - \left(V_{lam} - \frac{V_{lam}}{k} \right)^2 \right] \tag{3}$$

As the equation indicate, the pressure applied to the cantilever surface is determined by the velocity ratio k when the inlet air velocity is kept constant.

3. Modeling and optimization

Various bluff body configurations have been chosen for investigation to maximize the vortex induced pressure in the wake flow. Computational Fluid Dynamics (CFD) simulations were introduced to explain the vortex generation and to investigate their influence on the harvester performance. During the flow passing the bluff body the vortex is formed due to a partial inversion velocity gradient which are caused by the fluid drags [6]. The friction drag is formed by viscous shearing between the solid object and the fluid layer. It results a increasing velocity ratio *k* results and leads an internal kinetic energy loss along the length of bluff body.

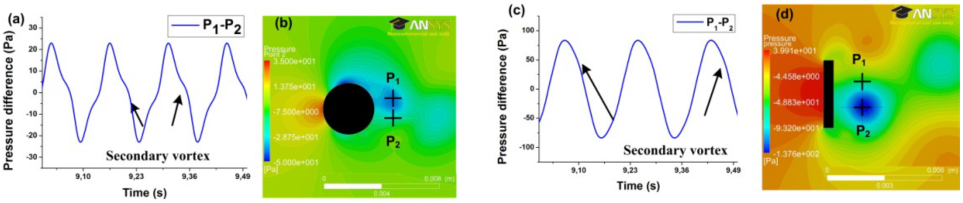

Fig. 2. Vortex pressure in the cylinder bluff body wake (a) and corresponding pressure distribution (b) compared with vortex pressure in the cuboid bluff body wake (c) and corresponding pressure distribution (d)

Therefore, to reduce the length, a cuboid-shaped bluff body is applied. Simultaneously, the sharp leading edge allows shifting the flow separation point into the direction of inlet to enhance the vortex pressure. The CFD simulation results show that with the application of a cuboid-shaped bluff body the vortex pressure in the wake reach 84 Pa at 2 m/s air flow (Fig. 2 (c)). This is approx. 4 times higher compared to cylinder shape bluff body (Fig. 2 (a)). In the simulation results, the shedding of a secondary vortex is observed, which is traveling after the main vortex (Fig. 2 (a) and (c)). It has been considered as additional damping, which lead a reduced harvester performance.

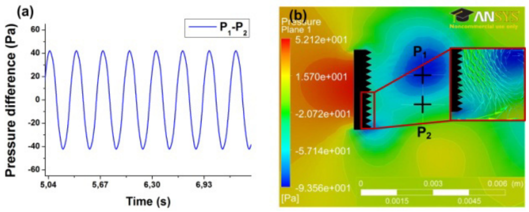

Fig 3. Vortex pressure in the comb-shaped bluff body wake (a) and corresponding pressure distribution with velocity vector (b)

For further optimization, a comb-shaped bluff body is introduced to inhibit the secondary vortex generation. Due to the pyramid cone structures at the backside of the comb shaped bluff body, the inverse rotational flow component is partially reduced from the crossover flow rather than completely interrupts it. Consequently, it reduces the secondary vortex induced pressure in the wake without dramatic pressure loss (Fig. 3).

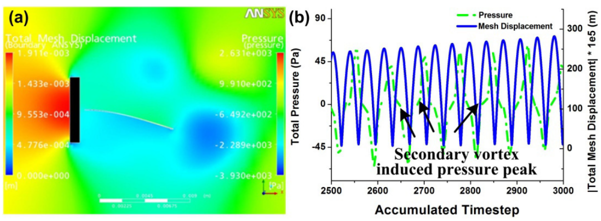

Fig. 4. Pressure distribution and cantilever deflection (a); vortex pressure at the cantilever and corresponding deflection (b).

To describe the interaction between the cantilever transducer and air flow, a two-way Fluid Structure Interaction (FSI) model is introduced (Fig. 4 (a)). A cantilever structure is placed in the wake behind the bluff body. The deflection of the cantilever at an air flow inlet velocity ramped from 0 m/s to 2 m/s is shown in Fig. 4 (b). Under

2 m/s air flow, the 9 mm piezoelectric PVDF cantilever shows a maximum deflection of 2.8 mm with the cuboid shaped bluff body. The simulation results confirmed that the secondary vortex has an influence on the cantilever transducer and consequenmtly on the energy conversion.

4. Experimental validation

Based on the simulation results, a demonstrator steup was assembled. It consists of a cuboid-shaped aluminum bluff body and a piezoelectric polymer (PVDF) cantilever transducer in size of 60 mm x 12 mm x 52 µm (DT2-052k from MSI). The demonstrator was tested in a self-assembled test bench, which shown in Fig. 5 (a).

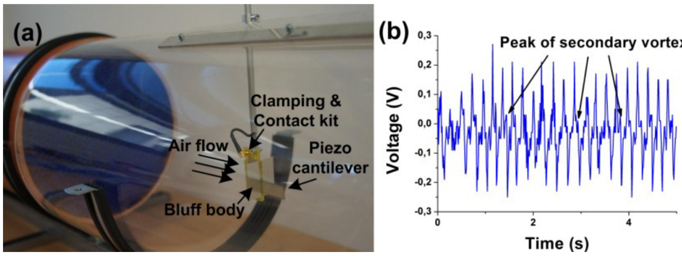

Fig. 5. Experimental test bench (a) and measured voltage output at 2 m/s air flow at a 100 kΩ resistor load (b)

The air flow is generated by a fan and regulated to a low turbulence level through a honeycomb fluid filter. As the air flows across the bluff body (33 mm x 12 mm x 1 mm), a cantilever vibration is induced because of the vortices and excites the specific vortex shedding frequency corresponding to the eigenfrequency of the cantilever which is 5 Hz. Due to the piezoelectric effect charges are generated as a consequence of the occurring mechanical strain. The resulting voltage is measured at a resistor load by an oscilloscope. The air flow velocity is adjusted to 2 m/s in the test section.

The measured output voltage at a 100 kΩ resistor load is shown in Fig. 5 (b). It can be seen, that the demonstrator generates a peak to peak voltage of about 0.4 V and a power of more than 1 µW. As previously predicted in the simulation, a secondary vortex is observed in the output signal, which is a small voltage peak behind the main peak.

5. Conclusion

A fluid kinetic energy harvester based on VIV has been proposed. The vortex induced pressure has been indentified as crucial parameter for the harvesting performance. Aiming for the enhancement of vortex induced pressure, a cuboid-shaped bluff body is presented. The CFD simulations show that the pressure is increased 4 times higher compared to a cylinder-shaped bluff body. Additionally, a secondary vortex has been observed in the wake flow and FSI simulations confirmed its negative influence on the electrical output. The comb-shaped bluff body reduces the secondary vortex generation without serious loss of primary vortex pressure.

The experimental result shows, that a demonstrator (33 mm x 12 mm x 30 mm) is able to gerate 0.4 V peak to peak voltage output at a 100 kΩ resistor load at an air flow of 2 m/s, which corresponds to a power of more than 1 µW. The predicted secondary vortex could be observed in experiments as well.

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